NASA TECHNICAL TRANSLATION NASA TT F-15,958

CONTRIBUTIONS OF THE DFVLR TO THE INVESTIGATION OF RESCUE AND RECOVERY SYSTEMS

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Translation of: "Beitraege der DFVLR zur Untersuchung von Rettungs- und Bergungssystemen," Zeitschrift fuer Flugwissenschaften, Vol. 22, May, 1974; pp. 153 - 163.

(NASA-TT-F-15958) CONTRIBUTIONS OF THE DFVLR TO THE INVESTIGATION OF RESCUE AND RECOVERY SYSTEMS (Scientific Translation Service) 30 p HC $4.50 CSCL 01C

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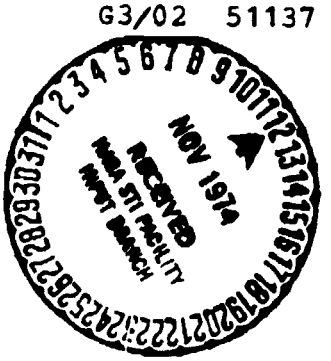

NATIONAL AERONAUTICAL AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546 OCTOBER 1974

CONTRIBUTIONS OF THE DFVLR TO THE INVESTIGATION OF RESCUE AND RECOVERY SYSTEMS*

Karl Friedrich Doherr and Peter Hamel**

1. Introduction

The technology and the relatively young science of parachutes /153*** are developing rapidly [1]. In aerodynamics, the large flight velocities made it necessary to use parachute systems and pilot ejector seats instead of simple parachutes. However, the large /154 loads which they are especially used for military purposes with parachutes, as well as the advance to higher altitudes, and recent requirement for recovering persons and loads from very low altitudes, have considerably increased the requirements for parachutes. Space flight has also extended the range of use for parachutes as far as velocity, altitude, and weight of recovered loads are concerned. We would like to mention the example of the recovery of the Apollo space capsules.

These requirements come from the above-mentioned areas as well as from meteorology and weapons technology. This has, in part, led to the development of very complicated systems to meet the requirements for performance, operational characteristics, and reliability. For example, in the case of pilot ejector

*This work was the basis of a paper entitled "Parachute Systems of the DFVLR for Stabilization and Recovery of projectiles" presented at the German Society for Aerodynamics and Space Flight (DGLR) symposium entitled "Takeoff and Recovery Methods for Projectiles, High Altitude Rockets, and Drones" held April 30, 1974, in Bremen, West Germany.

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***Numbers in margin indicate pagination of foreign text.

systems, or recovery systems for space flights, these systems consist of several stages of different parachutes and a large number of mechanical, pyrotechnic, and electronic components.

The DFVLR Institute for Flight Mechanics in Braunschweig is especially well suited to deal with problems in the area of recovery and rescue systems. In addition to its primary goal of working on projects for civilian and military projects, the institute is the only facility in West Germany which carries out scientific work in this area.

2. Notation

a	m/sec	speed of sound in air
c_l	N/m	spring stiffness of the parachute cord material
C_T	–	tangential force coefficient (= T/S_q)
C_N	–	normal force coefficient (= N/S_q)
d	Nsec/m	damping constant of the parachute cord material
D	m	reference diameter of the parachute cap
D_p	m	instantaneous projected diameter of the parachute cap
D_0	m	nominal diameter of parachute cap
F	N	filling force
$F(\alpha)$	–	aerodynamic force function
g	m/sec²	acceleration of gravity
H	m	altitude
I_y	kg m²	moment of inertia of the parachute load system, referred to the common particle P
K_0	1/sec	amplification factor $[= (\mu/\tau)(1 + m l_K^2/I_y)]$
l	m	distance between cap center of pressure and load
L_s	m	parachute cord length
m	kg	(inertial) total mass $(= m_L + m_K + m_{KH})$
m_K	kg	(weight) mass of the parachute cap

m_{KH}	kg	(hydrodynamic) mass of the air moved by the parachute cap
m_L	kg	(weight) mass of load
n	–	number of parachute cords
n_K	–	number of parachute caps of one group
N	N	normal force coefficient
q	N/m^2	stagnation pressure $(= \varrho v^2/2)$
R_f	m	coordinate of the parachute cap trajectory
s	1/sec	Laplace variable $(= \sigma \pm i\omega)$
S	m^2	cap area or reference area $(= (\pi/4) D^2)$
S_0	m^2	nominal cap area or reference area $(= (\pi/4) D_0^2)$
t	sec	time
T	N	tangential force coefficient
v	m/sec	trajectory or incident velocity
v_e	m/sec	stationary descent velocity
v_s	m/sec	velocity of the load during extension shock
α	°	angle of attack
α_e	°	stationary angle of attack (glide point)
$\zeta_\infty\ \omega_\infty$	1/sec	damping for $(\alpha) = 0$
μ	–	flight mechanical mass $(= 2m/\varrho S l)$, or mass coefficient $(= m/\varrho D_0^3)$
ν	m^2/sec	kinematic viscosity
ϱ	kg/m^3	air density
σ_m	N/m	meridianal stress
σ_μ	N/m	circumferential stress
τ	sec	flight mechanical time variable $(= l/v_e)$
ω_0	1/sec	frequency for $F(\alpha) = \infty$
ω_∞	1/sec	frequency for $F(\alpha) = 0$
WOK		root locus method

3. Scientific Investigations

3.1. Scale Influences

For many years, it has become possible to quite accurately predict the aerodynamic and flight mechanical properties of new developments in the aerodynamics of aircraft. However, parachutes and parachute load systems were not covered by theoretical models for a much longer time. This is due partially to the large shape changes which the parachute experiences during deployment. During this phase, the Reynolds number which is very important for the aerodynamic conditions changes by several orders of magnitude, when referred to the instantaneous diameter. The flow which first is attached to the slender cap which is filling later on becomes almost completely separated and turbulent (Figure 1). Also, during the stationary phase which follows the unfurling phase, the parachute drops with approximately a constant velocity, but the model laws for rigid bodies can only be applied conditionally, because there /155 is a continuous interaction between the pressure distribution and the shape of the cap. The form of the flexible parachute cap depends on the pressure distribution and vice versa. Therefore, the aerodynamic conditions of a flexible parachute become extremely complicated over a wide Reynolds number and Mach number range.

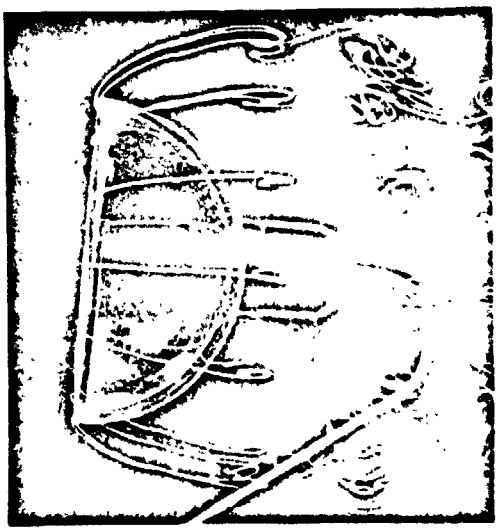

Figure 1. Separated flow along a rigid, hemispherical parachute cap in a water tunnel (from [4]).

For this reason, in order to describe the physical conditions, in addition to the well-known model coefficients such as the Reynolds number, Mach number, and Froude number, it is necessary to consider four additional coefficients (Table 1). In particular, the mass coefficient μ is especially important, which specifies the size of the parachute compared with the weight of the attached load. Also, the velocity ratio v_s/v_r is important, which is the velocity of the system at the time of the elongation shock divided by the subsequent stationary descent velocity.

TABLE 1

MODEL AND SIMILARITY PARAMETERS FOR PARACHUTE PROPERTIES AND PERFORMANCES

Reynolds number	$\frac{v D_0}{\nu}$
Mach number	$\frac{v}{a}$
Froude number	$\frac{g D_0}{v_s^2}$
Mass coefficient	$\frac{m}{\varrho D_0^3}$
Velocity coefficient	$\frac{v_s}{v_r}$
Spring coefficient	$\frac{n c_f D_0^2}{m v_s}$
Damping coefficient	$\frac{n d D_0}{m v_s}$

Since 1968 and under a common research program between the United States and West Germany (Data Exchange Agreement DEA AF-68-G-7415), theoretical and experimental work has been in progress with the purpose of determining the scale influences on the properties of parachute performances and properties in a systematic way (Table 2). The common problem definition has been found to be very useful, and there is a continuous exchange of information between the two countries.

3.2. Filling Process

Using a method developed by K. H. Fu, it is possible to determine the most important characteristics during the unfurling, such as the filling time and filling force variation (Figure 2). For example, it is possible to compute the altitude loss during the unfurling of parachutes for humans and loads [2] (Figure 3).

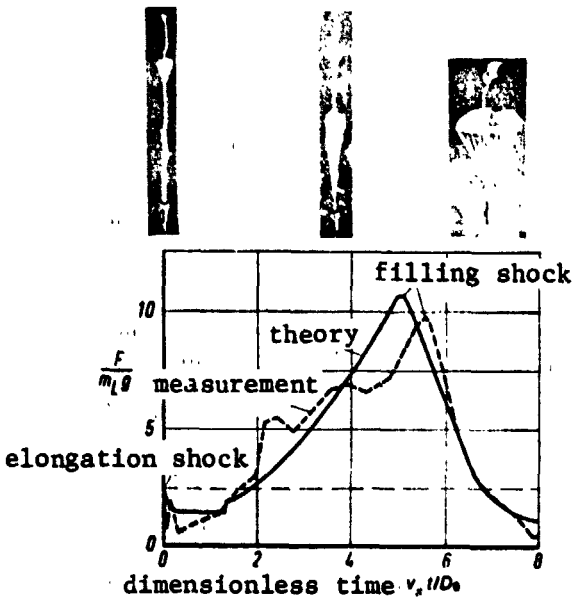

Figure 2. Time variation of the parachute filling force F $m_L g$ = load weight.

3.3. Drag and Stability

Using a special wind tunnel balance developed for flexible and rigid parachute models, a number of drag coefficients (C_W or C_T, respectively) as well as static stability derivatives (C_{Na}) ave been determined for various parachute types [3, 4, 5] (Figures 4 and 5). These parachute coefficients can be used for investigating the dynamic stability of parachute load systems, which are required for the analysis of complicated motion processes during the descent process.

For example, it has been shown that the general motion of a parachute load system during the descent is accompanied by pendulum oscillations, the frequency and damping of which primarily are influenced by the aerodynamic forces applied to the parachute cap. Since the aerodynamic coefficients of a large part of the present day parachute types depend on the

TABLE 2

WORKING PROGRAM FOR THE INVESTIGATION OF SCALE INFLUENCES IN PARACHUTES

- Model and similarity laws for flexible parachutes
- Calculation methods for
  Filling time
  Maximum forces during unfurling
  Dynamic stability
  Stress and strain distribution
- Wind tunnel and free flight experiments with model and original parachutes
- Data bank
- Analysis of the design and performance data and properties of parachutes
- Development of special equipment and test facilities for investigating parachutes

effective angle of attack of the parachute cap in a strongly nonlinear fashion, in each case, it must be determined whether the linear stability analysis generally used in aerodynamics is applicable [6, 7, 8].

In the following, we will discuss the example of a wide mesh parachute. Using the root locus curve method (WOK method) known from control theory, we will develop information regarding the stability behavior of a parachute load system for both small and large perturbations [7].

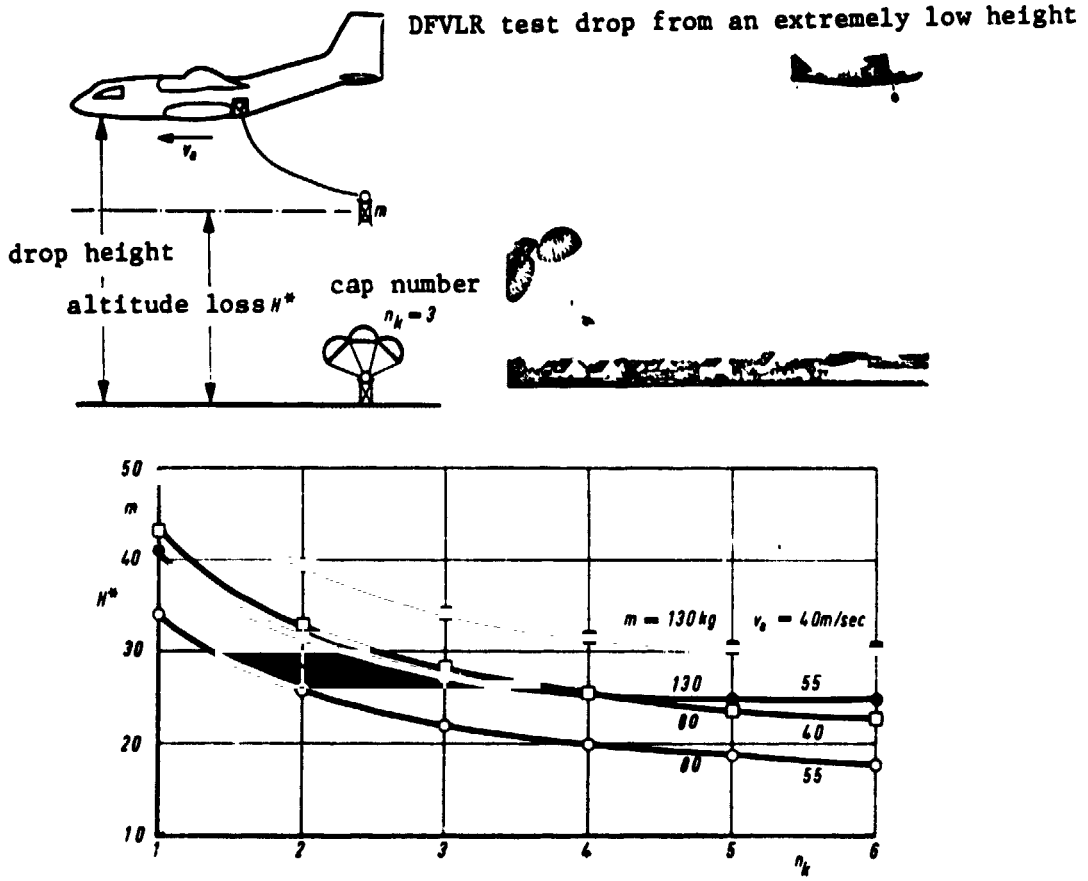

Figure 3. Parachute systems flor low drop height (from [2, 18],. m = total mass; v_a = drop velocity.

Figure 6 shows typical normal and tangential aerodynamic forces of a wide mesh parachute. The nonlinear variation of the normal force $C_N(\alpha)$ leads, in the case of small perturbations, and for a stationary angle of attack α_e, to a stable equilibrium state. In this case, the parachute load system drifts to the side with the trajectory angle α_e -90°. The static stability which develops at the so-called glide point α_e is determined by the normal force gradient $C_{N\alpha}$. This value

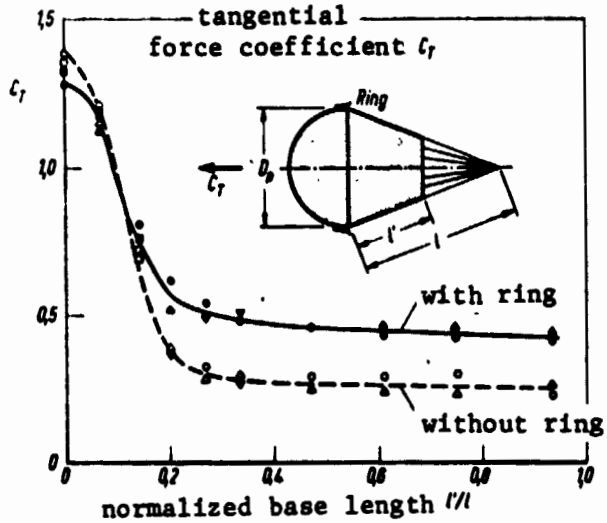

Figure 4. Influence of cap shape on the tangential force coefficient C_T, rigid model (from [4]).

represents a necessary but not at all sufficient condition, as will be shown later on, for dynamic stability of the system.

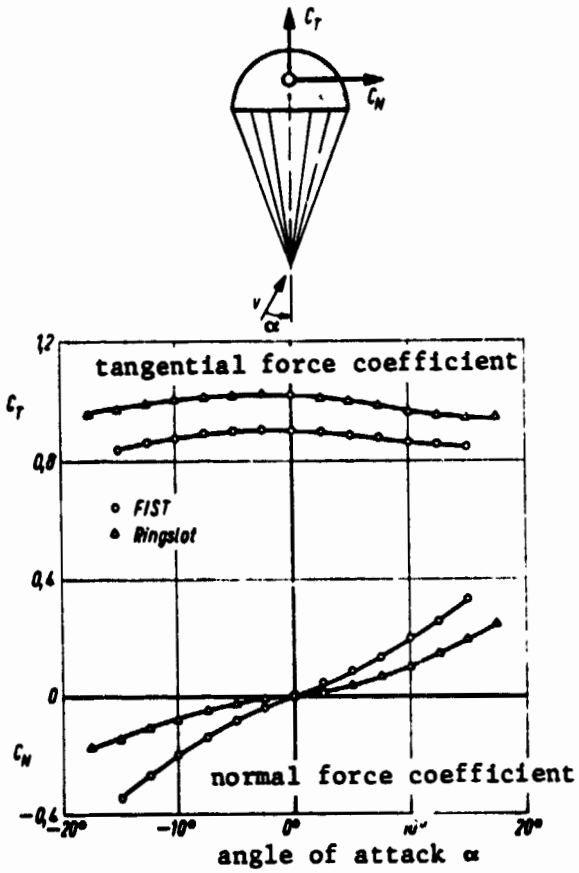

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Figure 5. Tangential and normal force coefficients of flexible parachute models (from [3, 5]).

The stationary descent velocity v_e at the glide point α_e can be determined from the relationship

$$v_e = \sqrt{\frac{2(m_L + m_K)g}{\varrho C_{T_e} S}}$$

The influence of the normal force $C_N(\alpha)$ on the dynamic behavior of a parachute load system can be depicted very clearly using the aerodynamic force function $F(\alpha)$ in the root locus plane (Figure 7). This aerodynamic force function

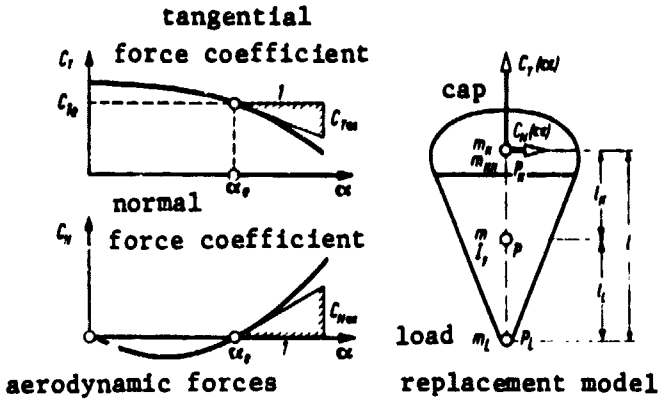

Figure 6. Aerodynamic forces and replacement model of a parachute load system (from [8]).

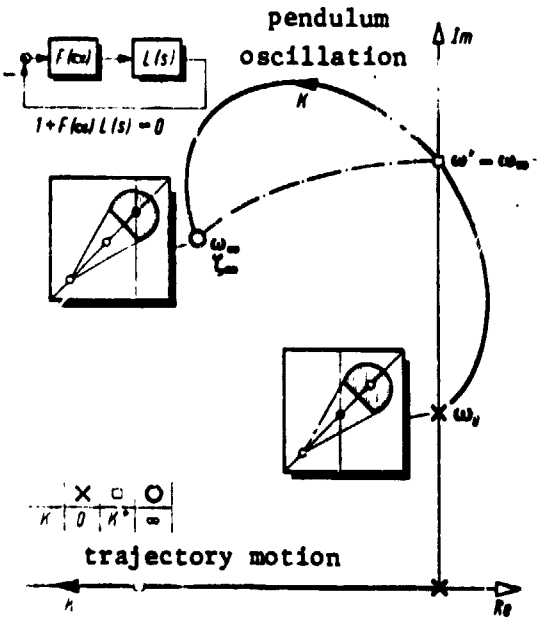

Figure 7. Dynamic stability of a parachute load system. WOK analogy: definitions (from [8]).

$F(s)$ $C_N(s)/\alpha$ aerodynamic force function

$L(s) = K_0 \frac{s^2 + 2\zeta_\infty \omega_\infty s + \omega_\infty^2}{s(s^2 + \omega_0^2)}$ transfer function

$K = F(s) K_0$ WOK amplification factor

$K' = \frac{\omega_\infty^2 - \omega_0^2}{2\zeta_\infty \omega_\infty}$ stability limiting value

represents, together with the parachute load transfer function L(s), which can be easily derived from the equations of motion, an equivalent single loop control loop, which represents the stability behavior of the parachute load system during descent as a function of the cap aerodynamics $F(\alpha)$. The corresponding singularities (poles and zeroes) of the parachute load transfer function describe certain physical limiting cases. The complex pair of poles $(s = \pm i\omega_0)$, for example, defines an undamped pendulum oscillation around the common point mass P for zero normal force $(C_N(\alpha) = 0)$, whereas, the complex pole pair $(s = -\zeta_\infty \omega_\infty \pm i\omega_\infty)$ represents a pendulum oscillation damped by centrifugal forces around the cap center of pressure P_K for extremely large cap aerodynamic forces $(C_N(s) = \infty)$.

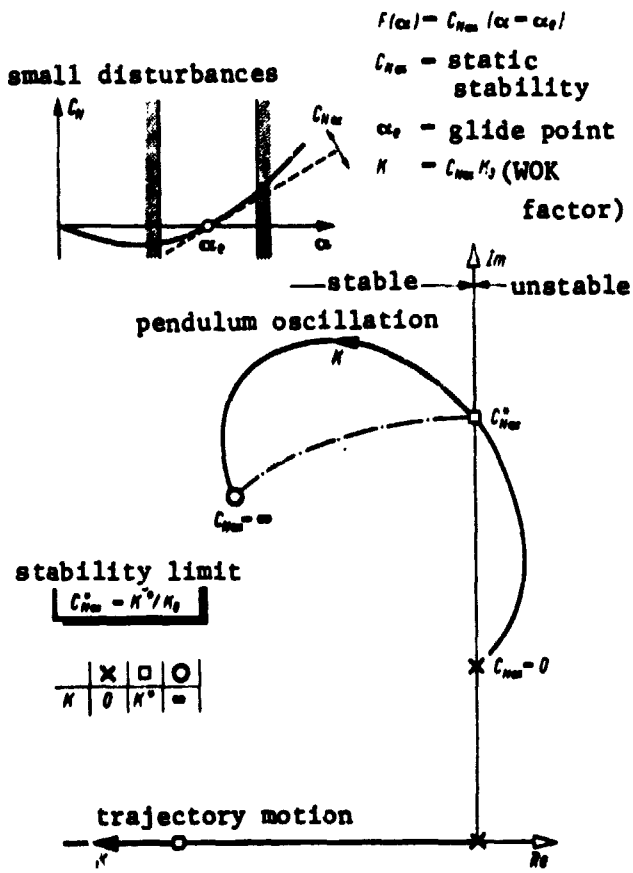

Figure 8. Dynamic stability of a parachute load system. WOK analogy: linear aerodynamics (from [7, 8]).

At the same time, Figure 7 can also be used to find the formula relationship for the critical WOK amplification factor K^*, at which the cap aerodynamic forces $F(\alpha)$ make the parachute load system start to perform undamped pendulum oscillations at the frequency $\omega^* = \omega_{\kappa}$.

If we first consider only the stability analysis for small perturbations, then the parachute stability will depend decisively on the local inclination $C_{N\alpha}$ at the glide point α_e [8]. In this case, the variation of the values (pendulum oscillati id trajectory motion) is dete ied as a function of $C_{N\alpha}$ (Figure 8).

It is apparent that, in order to maintain dynamic stability, it is necessary for the static stability $C_{N\alpha}$ to be greater than the critical value $C_{N\alpha^*}$. This stability limiting value can be determined from the relationship

$$C_{N\alpha}^* = K^*/K_0$$

where

$$K_0 = \frac{\mu}{\tau}\left[1 + m l_K^2/I_y\right],$$

$$\mu = 2m/\rho S l$$

and

$$\tau = l/v_e$$

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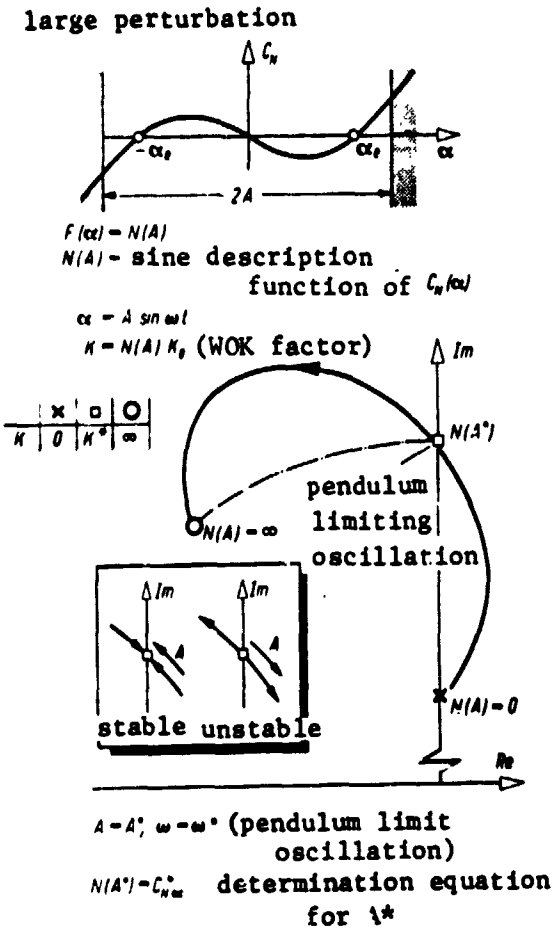

Figure 9. Dynamic stability of a parachute load system. WOK analogy: nonlinear aerodynamics (from [7, 8]).

If the perturbing amplitudes exceed a certain value, then the nonlinear variation of the normal force will produce a new motion. The steep gliding motion specified by α_e for small perturbations of the parachute load system is transformed into a vertical descent, which is accompanied by nonlinear pendulum limit oscillations at large amplitudes [7]. The frequency ω^* or oscillation period T^*, as well as the amplitude A^* of the pendulum limit oscillations can, in this case, be determined from simple formulas (Figure 9). The nonlinear normal force $C_N(\alpha)$ is then no longer stressed by the local inclination $C_{N\alpha}$ at the glide point, but by the amplitude-dependent sinusoidal description function N(A). Whereas the frequency ω^* is identical with the one obtained for small oscillations for the stability limit value $C_{N\alpha}{}^*$, the frequency ω^*, the amplitude A^* is determined from the equation

$$N(A^*) = C_{N\alpha}{}^*.$$

As an example, let us describe the variation of the normal force for the wide mesh parachute using the relationship

$$C_N(\alpha) = \frac{1}{2} C_{N\alpha} \left[\left(\frac{\alpha}{\alpha_e} \right)^3 - 1 \right] \alpha$$

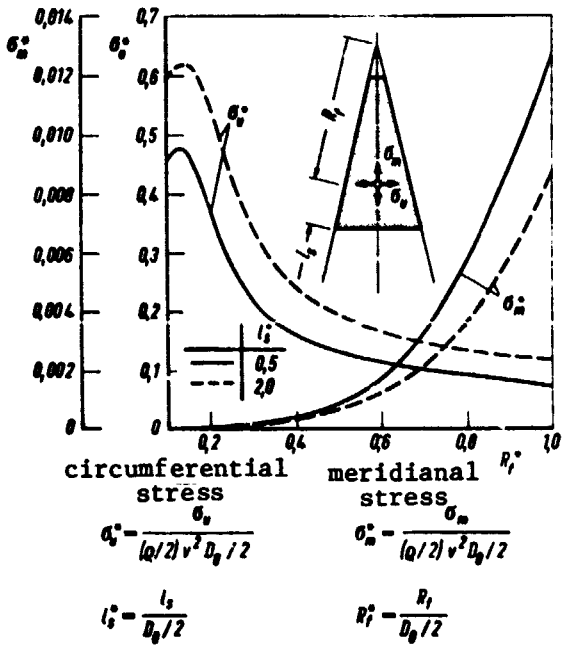

Figure 10. Calculated circumferential and meridianal stresses over a parachute cap trajectory (from [10]).
R_f = cap trajectory coordinate;
l_s = line length.

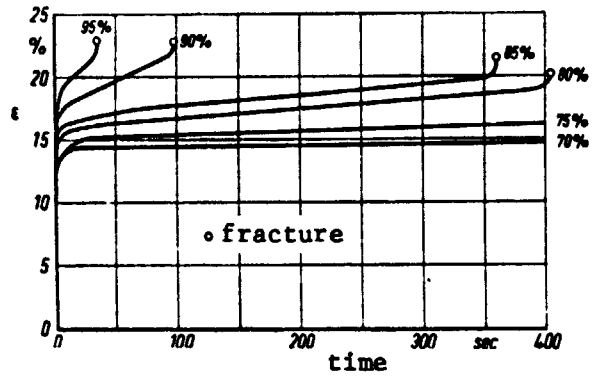

Figure 11. Creep strain ε up to fracture for 70 to 95% of fracture load for short time loading (from [11]).

The corresponding sinusoidal description function is

$$N(A) = C_{N\alpha}\left[\frac{3}{8}\left(\frac{A}{\alpha_e}\right)^2 - 1\right].$$

Using the equation for determining A* and the sinusoidal function of the normal force of the cap, it is possible to derive the amplitude A* of the pendulum limit oscillation:

$$\frac{A^*}{\alpha_r} = \frac{2}{\sqrt{3}}\sqrt{1 + 2\frac{C_{N\alpha}^*}{C_{N\alpha}}}.$$

In [8], the amplitude A* and the frequency ω* of the pendulum limit oscillation of a typical wide mesh parachute load system was calculated as a function of the local static stability $C_{N\alpha}$ according to the method described. This was compared with the numerical solution of a 2- and 3-degree of freedom system. Good agreement was found. Additional sample calculations were made for a number of other parachute types (Kostelezky, FIST, Ringslot, Circular Flat, Ribless Guide Surface).

3.4. Pressure Distribution and Strength

The pressure distribution over parachute caps [9] and the resulting stresses and deformations in the material were investigated both theoretically and experimentally. C. Saliaris [10] developed a method for calculating the cap shape and the meridianal and circumferential stresses in the elastic tissue of filled parachutes (Figure 10). A linear relationship between the stress and strain (Hooke law) was assumed which seems to be applicable for the low loads which occur in filled parachutes. The measurements published in [11] show that there is a much more complicated relationship between the stress and strain during the filling phase. In particular, the load rate (Figure 11), i.e., the duration within which the load maximum is reached, /159 is particularly important. It is found that, if the loading time is short, the tissue can support a higher load.

3.5. Free Flight Model Tests

In order to be able to systematically investigate the ranges of model coefficients μ and v_s/v_e and at the lowest possible cost, we developed a free flight test facility [12, 13] in which it was possible to investigate parachute load systems which were accelerated horizontally using a compressed air system (Figure 12). The parameter range which can be covered in the free flight facility practically covers the entire range over which parachutes are used. In this way, the required number of parachute experiments with aircraft and rockets will be able to be reduced in the future. Also, extensive test sequences are only possible with the free flight test facility.

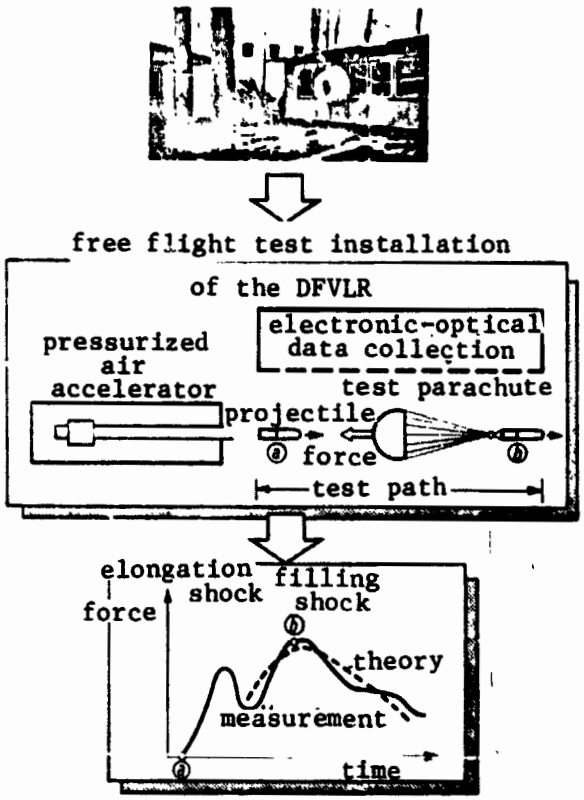

Figure 12. Free flight test facility (from [12]).

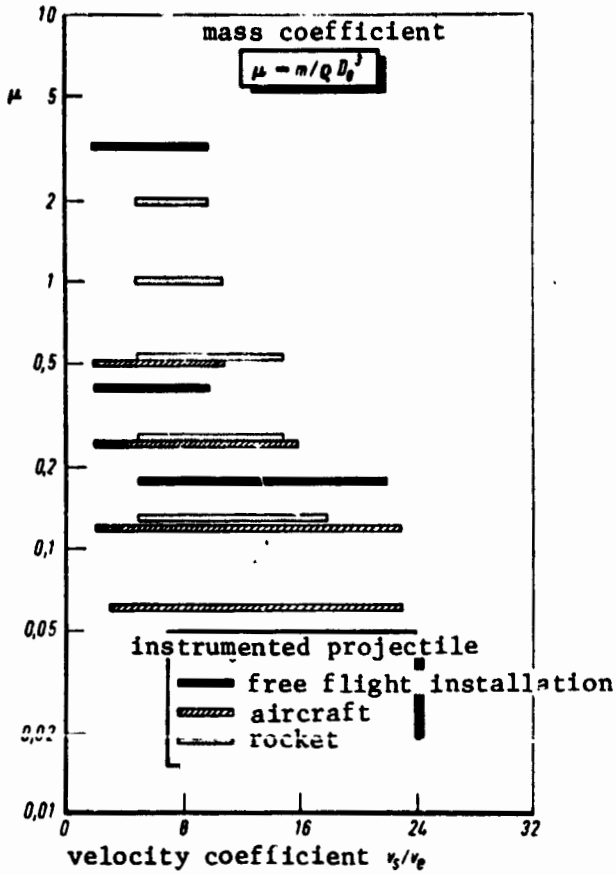

Figure 13. Ranges of the mass and velocity coefficient.

3.6. Data Bank

A data bank was established which is compatible with the U.S. Air Force Flight Dynamics Laboratory [14, 15]. The data bank stores the extensive theoretical and experimental results which are available at any time. In addition, this data can be stored on magnetic tape and can then be exchanged with the American partner.

3.7. Statistical Accident Investigations

Statistical accident investigations are very important for evaluating and improving recovery systems. For example, this

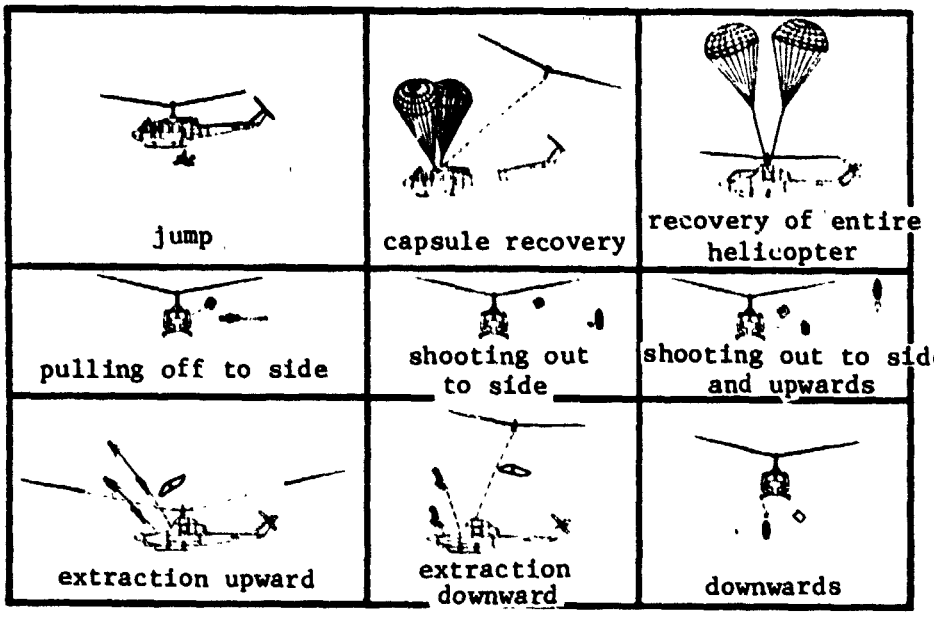

Figure 14. Rescue concepts for parachutes (from [16, 17]).

data shows for which flight maneuvers and flight attitudes it is necessary to have pilot ejection seats for rescue of crews. Recently, investigations regarding the possibility of rescue from combat helicopters have been made [16], because at the present time, no rescue possibilities are yet available for helicopter crews.

The AGARD Flight Mechanics Panel has set up a working group on escape measures for combat helicopter crews, with members from the various member states. The Institute for Flight Mechanics represented West Germany and, in the meantime, has written a report [17] on future possibilities for the rescue of helicopter crews (Figure 14).

4. Development and Testing of Parachute Systems

The Institute for Flight Mechanics has developed parachute systems corresponding to the requirements of the various ministries and industry for both civilian and military applications, /160 based on the scientific data presented above. It has performed advisory services during the investigation of parachute accidents and pilot ejection seat accidents.

4.1. Special Test Equipment and Facilities

In order to be able to carry out measurements with parachutes and parachute systems, we developed special test units and facilities. Of these we have the three component balance already mentioned (see Section 3.3) as well as the free flight test facility (see Section 3.5). There is also a family of instrumented projectiles with a weight between 5 and 500 kg (Figure 15). For example, we measured the forces in the parachute line during the expansion and filling of a parachute, the pressure distribution over the parachute cap, the change of the parachute shape during filling, and the velocity variation [1]. The forces and pressures were converted by the measurement transducers developed at the Institute for Flight Mechanics into analog-electrical signals and these were directed to recording devices on the ground, using a telemetry installation. In order to determine the area of the parachute during the individual filling phases, the filling process is filmed during drop tests from the tail of the instrumented projectile using a high velocity camera. At the same time, the entire experimental process is filmed from the ground using an additional high velocity camera with additional cinetheodolite or radar. This will provide data regarding the measurement process sequence, the descent velocity, and the trajectory inclination angle.

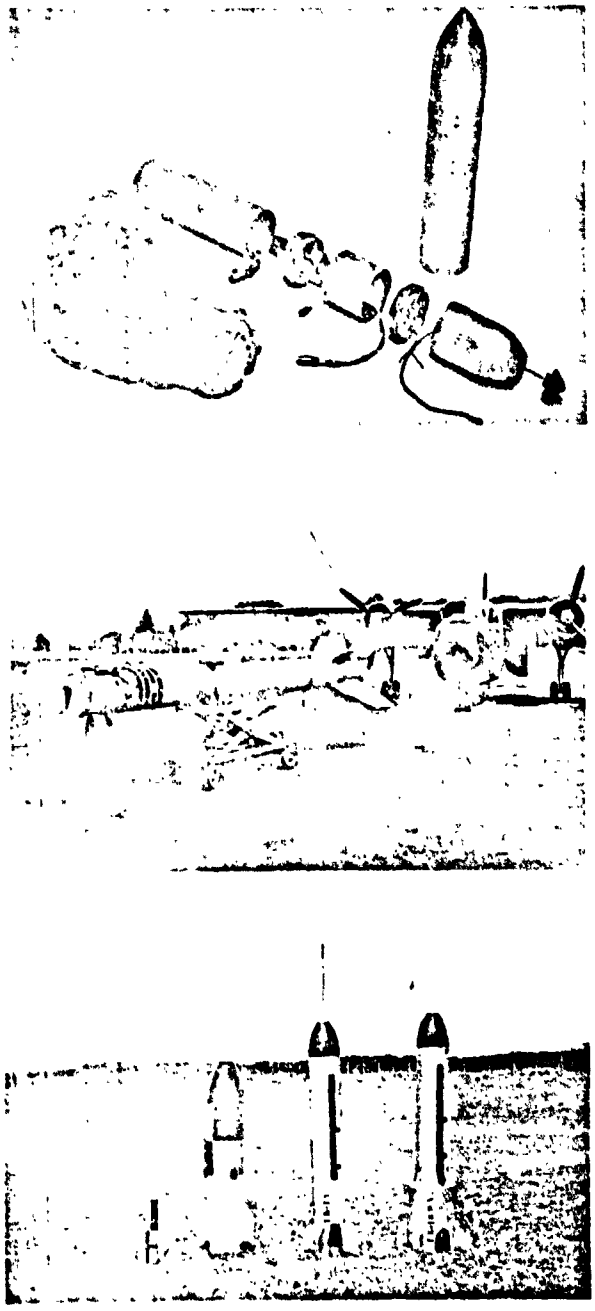

Figure 15. Instrumented projectiles of the DFVLR.

In order to accelerate the subsequent data processing, which up to the present required a great deal of time, very soon we will directly submit the measured values to an analog-digital process computer (type PDP 8 E). The same process computer will control the triggering of emergency parachute systems, in case they are required because of failure of the test parachutes.

4.2. Parachutes for Low Jump Heights

There is both civilian and military interest in crew parachutes, for which the altitude loss between the jump from the aircraft until a descent velocity of about 5 to 6 m/sec is reached is to be as small as possible. The occurring acceleration peaks should not exceed values which can be reasonably expected to be overcome by the parachute jumper.

The possibilities for reducing the altitude losses are being investigated both theoretically and experimentally at the Institute for Flight Mechanics

[2, 18]. It was found that it is more advantageous to use a collection of three small parachutes instead of a single large parachute, where the total drag of the collection of three is the same. The smaller parachutes of the group fill much more rapidly and, therefore, lead to deceleration much faster than a single corresponding large parachute (Figure 3). The investigations have shown that it is possible to develop a parachute system for drop heights of about 30 meters, so that the altitude between the point where the aircraft is left up to where the package opens can be limited by suitable constructive measures (opening lines). Also, there will be rapid filling by using a collection with several parachute caps, an increase in the touchdown velocity, and optimization of the parachute line length.

4.3. Rescue Systems for Crews of Fighters and Helicopters

At the request of the German Ministry for Defense, continuous investigations for improving the safety and reliability of rescue systems are being carried out. This is concerned with the reduction in the number of human lives lost and is therefore a particularly important problem. Correspondingly, these problems are assigned short time priorities over other continuing research projects. At the present time, there is a universal /161
recovery parachute for a velocity range between 80 to 450 km/hour which is being developed for various rescue systems. By using special elastic cloth, the filling time is extended at high stagnation pressures and, in this way, the filling shock force is reduced. The other usual measures for reducing the filling shock, which reduce reliability, such as for example, the short time reefing of the base using reef lines and reef line separators, are avoided.

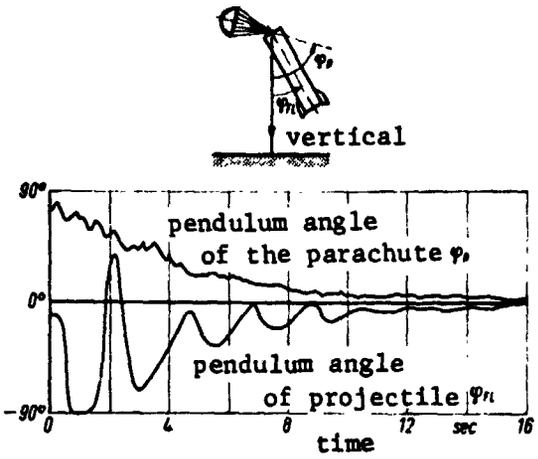

Figure 16. Decay of pendulum oscillations of a projectile after being turned around and braked by a stabilization parachute.

4.4. Systems for Braking and Stabilizing Projectiles

The braking and stabilization of military loads and projectiles using parachutes has been investigated for more than thirty years. Over the past few years, the Institute for Flight Mechanics has particularly addressed itself to the problem of braking fast projectiles using parachutes and then stabilizing them in such a manner that they will descend to the ground without performing pendulum motions. Figure 16 shows the decay of the pendulum motion of a projectile parachute system.

4.5. Recovery Systems for Space Flight

Even though several recovery systems have been developed in the U.S.A. for several specific tasks, it was found that the procurement of complete recovery systems from foreign countries is connected with a great deal of difficulty.

The Institute for Flight Mechanics, therefore, was involved in many ways in the development of recovery systems for space flight. The tasks were defined from space flight projects of the DFVLR and from industry (Dornier, MBB). In many instances, we were able to take advantage of our experience in dealing with military projects.

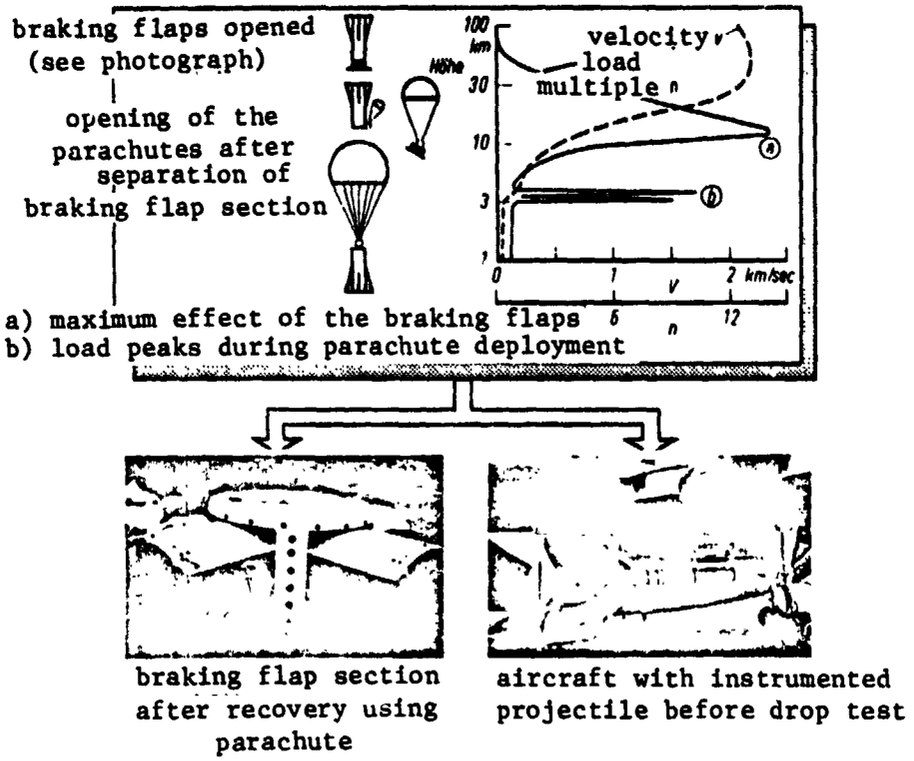

Figure 17. Recovery system for the propulsion stage of a high altitude research rocket.

4.5.1. Recovery system for stabilized payloads and expended stages of high altitude research rockets

In general, during the recovery of payloads from high altitude research rockets, the center of gravity is located such that the payload will carry out a flat spin motion during re-entry into the atmosphere. In this way, the aerodynamic drag is sufficient to decrease the payload velocity down to between 100 and 200 m/sec, at which point the parachute is triggered.

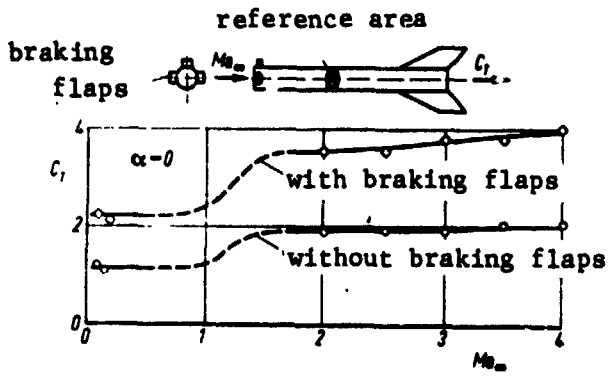

Figure 18. Tangential force coefficient C_T of a rocket motor model with and without braking flaps as a function of the incident Mach number Ma_∞ (from [19, 20]).

There exist a large number of cases in which the payload is stabilized by an extreme center of gravity position, stabilization fins, or by spinning around the longitudinal axis. In this case, the aerodynamic drag is so low that the velocity after re-entry is too high for deploying a parachute.

A multistage recovery system for stabilized payloads has been developed (Figure 17) for the mobile rocket base of the DFVLR. Its first stage consists of three braking flaps which brake the /162
system for deployment of the second stage, which consists of a FIST stabilization parachute. The third stage consists of a ring sail main parachute [19, 20] (Figure 18).

4.5.2. 1000-Pound SANDIA/NASA/DFVLR rocket payload water recovery system

Because of financial participation in the development costs, the DFVLR was able to obtain the rights for manufacturing and using a modern system for the recovery of rocket payloads for water landings. At the present time, the specifications required for German manufacture are being developed and tests are being prepared.

4.5.3. Recovery systems for projectile models of re-entry bodies

Free flight experiments with models have been carried out or planned by industry for investigating the dynamic behavior of various re-entry body configurations. The Institute for Flight Mechanics participated in the project Bumerang [21] and investigated recently the constructive measures for recovery of the flight model ART 24/LK 74, which weigh up to 500 kg.

5. Summary

The range of applications of parachute systems is, at the present time, being greatly expanded. At the Institute for Flight Mechanics of the DFVLR, in addition to the improvement and new development of personnel and recovery parachutes, we are also dealing with problems associated with the recovery of projectiles and payloads, also for extreme conditions. In addition to the demonstration of the dynamic stability of the parachute load system, we are also primarily interested in the stress distribution in the parachute cap required for strength analysis as well as scale influences. This information is required in order to derive the performance of full scale systems from data from model experiments. In addition to rescue from fighters, we are also investigating possibilities for rescue from helicopters. In addition, there is the military requirement for small drop heights. Using theoretical and experimental investigations, we are developing parachute systems for this application as well.

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Translated for National Aeronautics and Space Administration under Contract No. NASw-2483, by SCITRAN, P. O. Box 5456, Santa Barbara, California, 93108.